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Molecular Niobium Precursors in Various Oxidation States: an XAS Case Study

Maciej D. Korzyński,^{§,†} Luca Braglia,^{§,‡} Elisa Borfecchia^{a,b} Carlo Lamberti^{*c,d} and Mircea Dincă^{*,†}

[†] Department of Chemistry, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States

[‡] CNR-Istituto Officina dei Materiali, TASC Laboratory in Area Science Park - Basovizza, Strada Statale 14 km 163.5, 34149 Trieste, Italy

^a Department of Chemistry, NIS, CrisDi, and INSTM Centre of Reference, University of Turin, Via Quarello 15, I-10135 Torino, Italy

^b Center for Materials Science and Nanotechnology (SMN), Department of Chemistry, University of Oslo, 1033 Blindern, 0315 Oslo, Norway

^c Department of Physics, NIS, CrisDi, interdepartmental centers, and INSTM Centre of Reference, University of Turin, Via Giuria 1, I-10125 Torino, Italy

^d The Smart Materials Research Institute, Southern Federal University, 5 Zorge Street, Rostov-on-Don, 344090, Russia

ABSTRACT: Although X-ray absorption spectroscopy (XAS) has become an indispensable tool in characterization of solid-state materials, it is less of a staple in molecular chemistry of niobium. Scattering X-ray techniques remain relatively unexplored for the systematic study of molecular niobium compounds. Here, we use XAS to probe the niobium environment in commonly used Nb precursors in +V, +IV and +III oxidation states. Apart from laying out the guidelines for identification of niobium oxidation states, we correlate our data with density functional theory (DFT) models to provide further structural insight. Of particular note, we are able to shed light on the nature of the commonly-used and catalytically competent NbCl₃(DME), which had not been previously characterized structurally despite its prevalence in Nb chemistry.

INTRODUCTION

X-ray absorption spectroscopy (XAS) has become the workhorse characterization technique in solid-state chemistry.^{1,2} XAS spectra are comprised of two distinct regions: X-Ray absorption near edge structure (XANES) and extended X-Ray absorption fine structure (EXAFS). Together, they provide crucial information such as oxidation state, symmetry and coordination environment.³ The element specificity of the technique is often the only means available for the investigation of the intimate structure of non-crystalline materials and catalysts. In contrast, molecular chemistry heavily relies on single crystal X-ray diffraction (SCXRD)⁴ for structural insight. SCXRD has obvious advantages, but necessitates the production of single crystals, a non-trivial exercise that often suffers from solubility and/or reactivity issues.⁵

Niobium compounds find utility in material science,^{6,7} fundamental inorganic chemistry^{8–12} and catalysis.^{13–16} Such compounds must be accessed most often from well-defined molecular Nb precursors in several oxidation states. Specifically, niobium(V) chloride (NbCl₅), niobium(IV) chloride tetrahydrofuran complex (NbCl₄(THF)₂)¹⁷ and niobium(III) chloride dimethoxyethane adduct (NbCl₃(DME))¹⁸ are the most common starting materials for niobium chemistry in their respective oxidation state and even function as catalytically active species themselves. Their formulas, as written above and most often referred to in the literature, are somewhat misleading because only NbCl₅ has been structurally characterized and shown to exist itself in the solid-state as discrete Nb₂Cl₁₀ dimers.¹⁹ A body of spectroscopic and magnetic studies have suggested that NbCl₄(THF)₂ exists as a paramagnetic (d¹) monomer with THF molecules arranged in a *cis* fashion in the solid state with *trans* geometry observed in solution.^{20,21} For NbCl₃(DME), on the other hand, there is no definitive answer whether this complex exists in monomeric form, with conflicting reports describing it as either mononuclear²² or polymeric.^{23,24} The absence of a single crystal X-ray structure of this compound is most

likely a consequence of its high reactivity towards any solvent that it is soluble in.²⁵ A structural understanding would be valuable not only for the rational synthesis of other Nb(III) complexes, but also for comprehension of its catalytic performance, such as in [2+2+2] cycloadditions.²⁶⁻²⁹ All precursors would benefit from a rigorous description of their structures, given the current emphasis on precise engineering of materials at the atomic level, from custom materials synthesis to niobium doping.

XAS is well-suited to tackle this challenge. In this contribution we investigate the coordination environment of these niobium chlorides in +V, +IV and +III oxidation states, allowing us to settle a debate regarding the solid-state structure of these molecules aided by correlation with density functional theory (DFT) calculations. This approach, already successfully applied to understand the local structure of metal atoms in zeolites,³⁰ metal-organic frameworks^{31,32} and organometallic complexes,³³⁻³⁶ has been named *DFT-assisted EXAFS analysis*. Using this approach, when different structural models are considered, the selection of the most reliable structural model is based on: (i) the agreement between experimental and theoretical EXAFS curves (R-factor); (ii) agreement between DFT- and EXAFS-optimized interatomic distances; (iii) error bars associated with the optimized parameters and (iv) physical meaningfulness of the non-structural parameters (ΔE and σ^2).³⁷ Additionally, the XANES region is discussed to benchmark for further studies of oxidation state for new Nb containing species.

RESULTS AND DISCUSSION

We began our analysis by looking at Nb K-edge XANES spectra (Figure 1) of NbCl₅, NbCl₄(THF)₂ and NbCl₃(DME), which allow us to assign the oxidation state of niobium in each of these compounds as +V, +IV and +III, respectively. This assignment is based on the qualitative description of the XANES spectra supported by the literature.³⁸ A decrease in the edge energy can be observed for NbCl₃(DME) (18995.6 eV) compared to that of the higher valent Nb(IV) and Nb(V) precursors (18997.8 eV). This red shift is in line with the expected increase of the electron binding energy in higher oxidation states. In the spectrum of niobium(V) chloride a weak pre-edge shoulder centered at 18990 eV can be observed. This feature is related to an electronic transition from the 1s-orbital to the 4d-orbital manifold and has already been observed in niobium(V) oxide (Nb₂O₅).³⁹ A systematic study³⁸ of minerals containing Nb⁰, Nb²⁺, Nb⁴⁺ and Nb⁵⁺ ions utilizing Nb K-edge XANES has shown that the pre-edge feature is typically only seen for +5 and mixed valent +4/+5 and is absent for other oxidation states irrespective of geometry. Our analysis confirms that this trend also holds for Nb³⁺ species. All three chlorides show strong absorption peaks at approximately 19003 eV and 19013 eV. NbCl₄(THF)₂ and NbCl₅ distinguish themselves by the presence of an additional feature at 19018 eV and 19026 eV respectively, which is due to low energy scattering resonances of photoelectrons by neighbouring atoms.

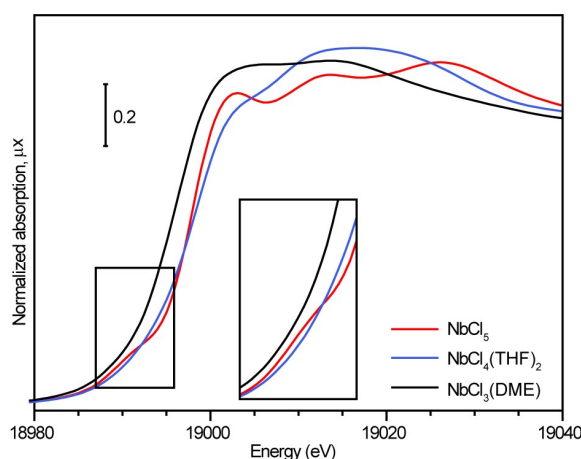


Figure 1. Nb K-edge XANES spectra of the investigated species.

The obtained EXAFS data (Figure S3) has excellent signal/noise ratio up to $k = 18 \text{ \AA}^{-1}$, which allowed us to elucidate the structure of the investigated compounds. The strategy that was adopted relied on the optimization of the possible structural models using density functional theory (DFT). These models served as starting points

for the fitting of the EXAFS signal. We began our analysis with the niobium(V) chloride, which was previously characterized by SCXRD studies,¹⁹ in order to validate our approach to data analysis. The DFT optimized model (Figure 2a) matched the reported crystal structure well (Table S2).

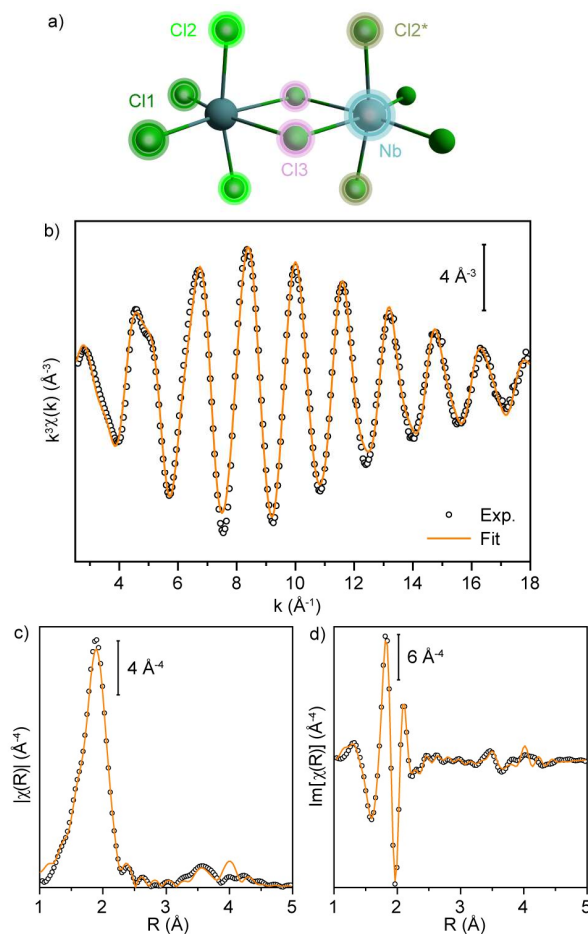


Figure 2. a) optimized DFT model of NbCl₅. b) k^3 -weighted EXAFS signal, and corresponding modulus (c) and imaginary (d) parts of the phase uncorrected FT of the experimental and best fit for NbCl₅.

For this and forthcoming analyses the amplitude reduction factor⁴⁰ (S_0^2) was fixed to 1. To reduce the number of independent parameters optimized in the fit, the single scattering (SS) and the multiple scattering (MS) paths were defined geometrically (for additional details see Supporting Information). We defined two Debye-Waller factors $\sigma^2_{\text{Cl1,2,2}^*}$ and σ^2_{Cl3} to account for a difference between terminal and bridging chlorides, respectively. The parameter correlation was monitored to avoid values bigger than 0.8 in absolute value. The obtained fit (for parameters see Table S1), using the NbCl₅ DFT-optimized model reproduces our experimental data well (Figure 2b-2d). Both Nb-Nb and Nb-Cl distances are in good agreement with both the DFT calculations and SCXRD data (Table S2). Interestingly, in the best-fit set of parameters the bridging chlorides seem to have a higher Debye-Waller factor than terminal ones. This may be related to peculiar vibration modes of the structure. Having established a successful data analysis methodology on NbCl₅, we next shifted our attention to the other niobium complexes, which structure could not be determined by SCXRD. In all cases the EXAFS fit was performed using an isotropic expansion coefficient⁴¹⁻⁴⁴ to reproduce the higher shell contributions (see Supporting Information).

For niobium(IV) chloride THF adduct both monomeric and dimeric structures were considered. As NbCl₄(MeCN)₂ is a related, structurally characterized monomeric compound⁴⁵ we used it as a template for DFT calculations (Figure 3a). A less common, but prevalent type of structure for ‘NbCl₄L₂’ stoichiometry (where L is typically a monodentate phosphine) is a dimeric [NbCl₂L₂]₂(μ -Cl)₄ face-sharing double square antiprism.^{46,47} We have optimized the structure of the analogous dimer for NbCl₄(THF)₂ in two spin states, singlet and triplet (Figures 3b and 3c, respectively), as expected in spin-symmetric systems arising from two

d^1 centers. The most striking differences between these two spin states is the considerable difference in the Nb-Nb distances (2.87 Å for singlet and 3.37 Å for triplet) concomitant with the formal single bond between the two metal centers in case of $S = 0$ system. Additionally, the singlet structure exhibits bridging chlorides equidistant from both Nb centers, as opposed to the triplet structure, which has two independent sets of Nb- $(\mu\text{-Cl})$ distances.

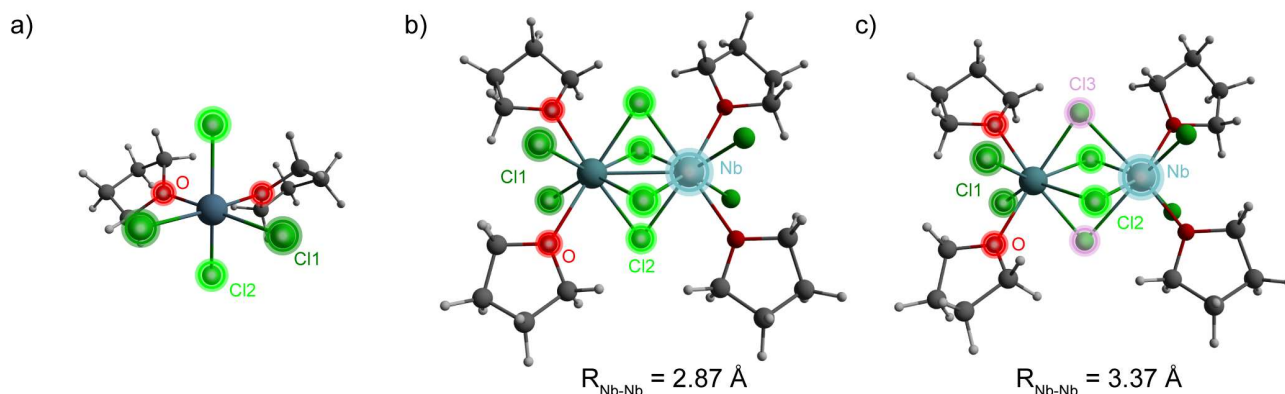


Figure 3. DFT-optimized structures for $\text{NbCl}_4(\text{THF})_2$ as a) monomer, b) singlet dimer and c) triplet dimer.

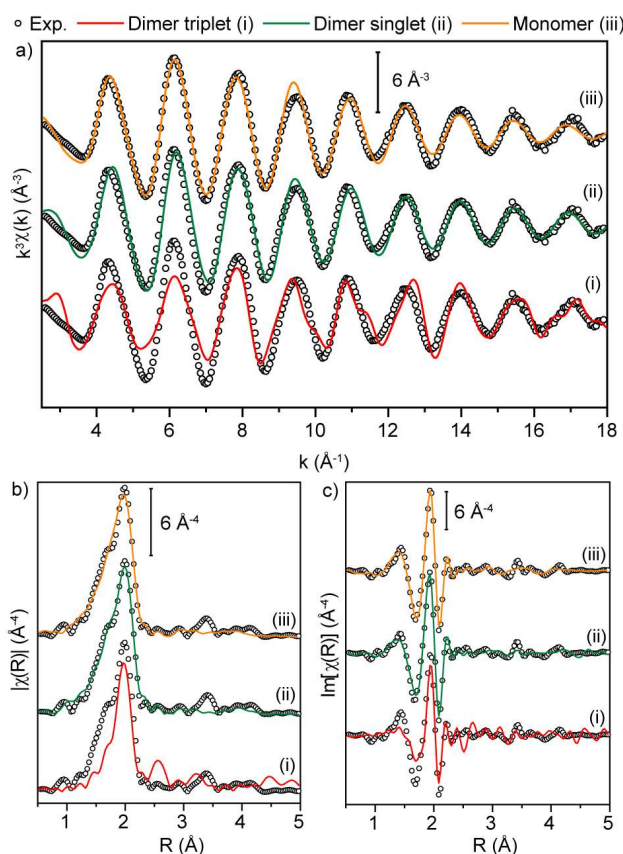


Figure 4. a) k^3 -weighted EXAFS functions. Corresponding modulus (b) and imaginary (c) part of the phase uncorrected FT. The experimental data and the best fits for the three different $\text{NbCl}_4(\text{THF})_2$ models.

An initial look at the correspondence of the obtained EXAFS signal and the fit (Figure 4) obtained using the dimeric model in the triplet state shows a poor match with an R-factor of 0.2 and unreasonably high ΔE value (15 ± 2 eV). Additionally, the σ^2_{O} and σ^2 are unphysically low ($0.0003 \pm 0.0006 \text{ \AA}^2$ and $0.0004 \pm 0.0031 \text{ \AA}^2$). While both fits for the monomeric structure and dimer in singlet configuration reproduce the experimental spectrum well up to 3 \AA , some of the minor features beyond the 1st coordination shell are difficult to be reproduced. A possible explanation involves contribution from neighboring molecules in the lattice, not factored in our non-periodic model. From the comparison of the EXAFS analysis obtained using these two models, several observations undermine the feasibility of the dimeric structure. An unexpectedly large compression of the Nb–Nb distance occurs ($2.28 \pm 0.02 \text{ \AA}$) compared to the DFT optimized model (Table S4). The same applies to the Nb–(μ -Cl) distances, which are also short compared to both the DFT model as well as the published distances for other face-sharing double square antiprismatic structures.⁴⁸ Very large EXSFS fitting errors for Nb–Cl and Nb–O bond distances underscore further inconsistencies with this model (Table S3). In light of the presented data our analysis supports the existence of $\text{NbCl}_4(\text{THF})_2$ in the solid state as a monomeric pseudo-octahedron with one unpaired electron contributing to its magnetic moment.

Finally, we investigated niobium(III) chloride dimethoxyethane complex, which has previously been described as both a monomer and a polymer, with no definitive experimental evidence distinguishing these possibilities to our knowledge. As a monomer, the d^2 niobium center could exhibit either singlet or triplet character (Figure 5a and 5b, respectively). Dimeric structures are also well-known for several Nb(III) halide complexes ligated with $\text{N}^{49,50}$, $\text{P}^{49,51,52}$ and $\text{S}^{53,54}$ donors. Thus, we have also optimized edge-sharing bioctahedral structures in singlet, triplet and quintet spin state (Figure 5c, 5d and 5e) based on the known crystal structures with bound acetonitrile. The most pronounced consequence of varying the spin state is expectedly the change in the Nb–Nb distance and the formal intermetallic bond order. Structures involving bridging DME ligands were excluded due to the fact that such coordination has only been observed in case of the smaller bite angle chelating ligands such as methylenebis(phosphine).⁵⁵

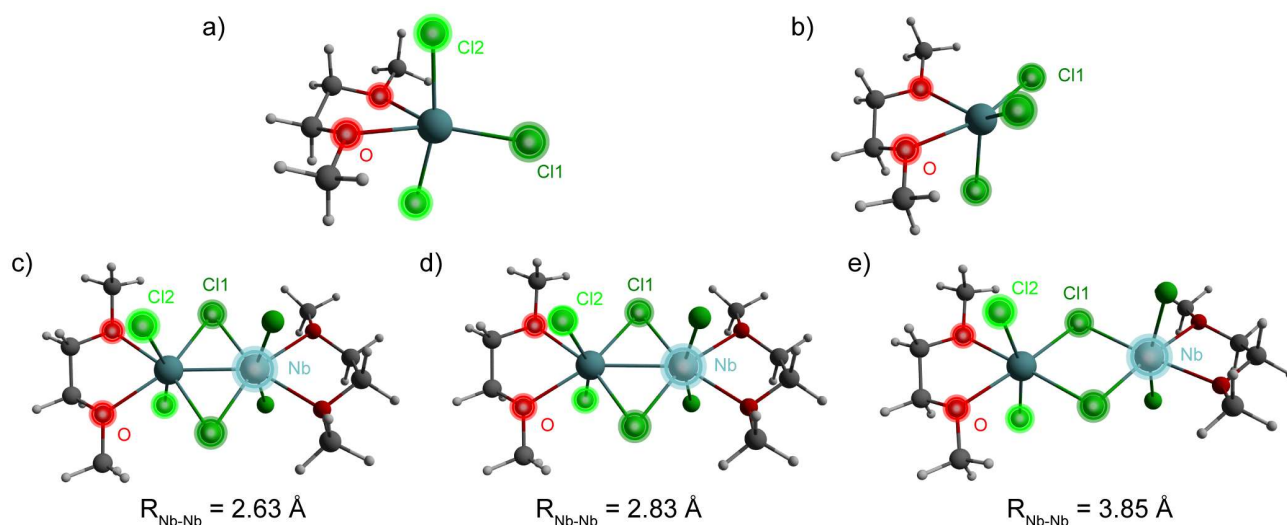


Figure 5. DFT-optimized structures for $\text{NbCl}_3(\text{DME})$ as a) singlet monomer, b) triplet monomer, c) singlet dimer, d) triplet dimer and e) quintet dimer.

Attempts to fit the EXAFS data using the optimized models (Figure 6) showed that both singlet and triplet monomeric models reproduced the experimental data poorly, as evidenced by high R-factors (Table S5). Moreover, the fit for the monomer in the singlet state had an unphysically high σ^2_{O} parameter (0.01 \AA^2) and large errors for σ^2_{O} and for both Nb–O and Nb–Cl_{1,2} interatomic distances (± 0.1 and $\pm 0.2 \text{ \AA}$, respectively). Similar instabilities in the fit for the monomer in the triplet state could be observed: large errors for α and σ^2 (± 102 and $\pm 120 \text{ \AA}^2$, respectively) and unphysical, negative σ^2_{O} . The quintet dimeric structure also reproduced the experimental spectrum poorly (R-factor is 0.05) with a very low value of σ^2_{Cl} ($0.0007 \pm 0.0007 \text{ \AA}^2$) and high σ^2_{O} ($0.01 \pm 0.02 \text{ \AA}^2$).

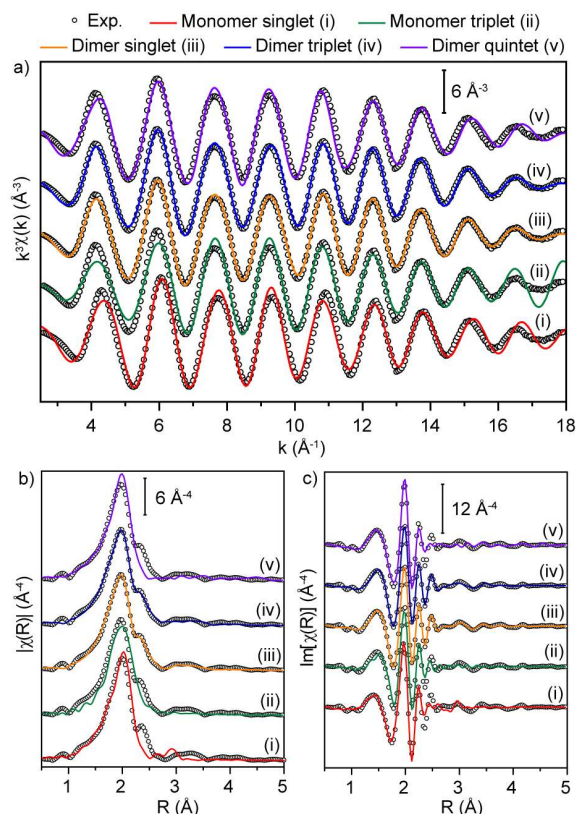


Figure 6. a) k^3 -weighted EXAFS functions. Corresponding modulus (b) and imaginary (c) part of the phase uncorrected FT. The experimental data and the best fits for the five different $\text{NbCl}_3(\text{DME})$ models.

We found that fits to the dimeric models in both the single and triplet states were a much better match with the experimental data. Based on the fit parameters, the singlet dimeric structure is more probable as evidenced by closer correspondence of the calculated Nb–Nb distances with the ones obtained from the fitting procedure (Table S6). The obtained distance (2.700 Å) also matches those of other singlet dimeric niobium species.⁴⁸ Notably, during the fitting for the triplet model, the Nb–Nb distance underwent contraction more in line with the one obtained from the optimization of the singlet structure. Additionally, the σ^2_{Cl} value for the triplet configuration is unreliably low ($0.0011 \pm 0.0003 \text{ \AA}^2$), further disfavoring the triplet state.

To further confirm the singlet spin state of the $[\text{NbCl}_2(\text{DME})]_2(\mu\text{-Cl})_2$ dimer we compared its computed Gibbs free energy at 298.15 K with that of the dimer in the triplet state. Although the singlet configuration was indeed lower in energy, it was preferred by only 0.7 kcal/mol, a difference too small to serve as incontrovertible proof for any of these two electronic configurations. Confirmation of the magnetic ground state came instead from vibrating sample magnetometry (VSM) measurements on $[\text{NbCl}_2(\text{DME})]_2(\mu\text{-Cl})_2$ and $\text{NbCl}_4(\text{THF})_2$ (Figure S4). For the latter the extracted effective magnetic moment ($\mu_{\text{eff}} = 1.73$ at 274 K) is in line with the expectations for a d^1 system. The same measurement performed on $[\text{NbCl}_2(\text{DME})]_2(\mu\text{-Cl})_2$ showed essentially diamagnetic behavior in line with $S = 0$ configuration. The combination of all of these techniques has led us to propose a reformulation of $\text{NbCl}_3(\text{DME})$ as $[\text{NbCl}_2(\text{DME})]_2(\mu\text{-Cl})_2$ in the solid state.

CONCLUSION

In this contribution we investigated simple niobium halide precursors commonly used in inorganic synthesis and catalysis. As $\text{NbCl}_4(\text{THF})_2$ and $\text{NbCl}_3(\text{DME})$ have proven difficult to analyze via single crystal X-ray diffractometry, we utilized DFT-assisted EXAFS analysis to gain insight into their solid-state structure. This technique, still underutilized in the molecular inorganic chemistry of niobium, allowed us to confirm the notion that the niobium(IV) chloride tetrahydrofuran adduct is monomeric in solid state. It has also allowed us to establish that the common and commercially available niobium(III) chloride dimethoxyethane complex does not exist in a monomeric form as previously assumed, but as a dimer akin to other niobium(III) halides ligated with N and P donors. XANES spectroscopy has been used to confirm the valence state of Nb.

ASSOCIATED CONTENT

Supporting Information

Experimental details, computational methods, detailed list of EXAFS fit parameters, magnetic measurement data and xyz coordinates for the optimized structures are available in the supporting information pdf file.

AUTHOR INFORMATION

Corresponding Authors

E-mail: carlo.lamberti@unito.it

E-mail: mdinca@mit.edu

Author Contributions

§ MDK and LB contributed equally.

ORCID

Maciej D. Korzyński: 0000-0002-6577-1821

Luca Braglia: 0000-0003-0796-3670

Elisa Borfecchia: 0000-0001-8374-8329

Carlo Lamberti: 0000-0001-8004-2312

Mircea Dincă: 0000-0002-1262-1264

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Notes

The authors declare no competing financial interests.

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